UCRL- 85009
PREPRINT

ELECTRIC ARC RADIUS AND CHARACTERISTICS

Ta-Ming Fang

This paper was prepared for submittal to the Thirty-third Gaseous Electronics Conference, October 7-10, 1980, Norman, Oklahoma

September 30, 1980

ELECTRIC ARC RADIUS AND CHARACTERISTICS

Ta-Ming Fang*

University of California
Lawrence Livermore National Laboratory
Livermore, California 94550

*Permanent Address: Dept. of Aerospace and Mechanical Engineering
Boston University, Boston, Massachusetts 02215

LLNL Summer Visiting Faculty

Electric Arc Radius and Characteristics*

ABSTRACT

The heat transfer equation of an arc discharge has been solved. The arc is assumed to be a cylinder with negligible axial variation and the dominant heat transfer process is conduction radially inside the column and radiation/convection at the outside edge. The symmetric consideration allows a simple one-dimensional formulation. By taking into account proper variation of the electrical conductivity as function of temperature, the heat balance equation has been solved analytically. The radius of the arc and its current-field characteristics have also been obtained. The conventional results that $E \sim I^{0.5385}$ and $R \sim I^{0.7693}$ with E being the applied field, I the current, and R the radius of the cylindrical arc, have been proved to be simply limiting cases of our more general characteristics. The results can be applied quite widely including, among others, the neutral beam injection project in nuclear fusion and MHD energy conversion.

*Work performed under the auspicies of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

I. INTRODUCTION

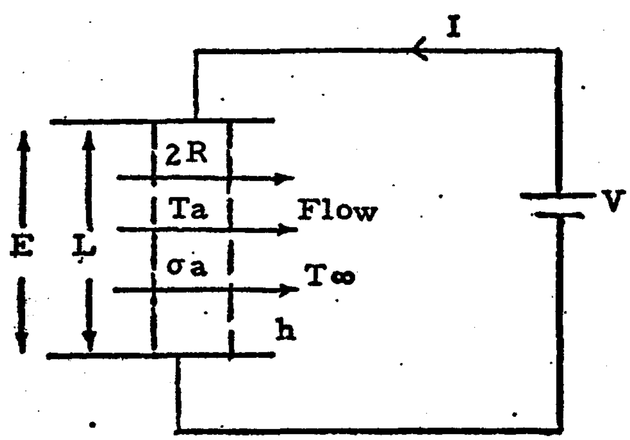
The electric arcing phenomenon has been known for almost as long as the history of mankind, predominantly in the form of lightning. Recent interests in arcing come, however, basically from its formation in modern industry and energy technology. For instance, the wearing away of the electrodes in MHD generators or any sparking plugs or the make-and-break contacts in the ignition systems in internal combustion engines are typical examples of the damages caused by the formation of arcs. They affect not only the lifetime of the electrodes but also the current transport, power output, and the overall performance of the generator.

In the magnetic fusion energy development, in order to increase plasma density, neutral beam injection[1,15] is needed. Arcing becomes a serious problem in not only the ion extraction and acceleration section of the injector but also the discharge chamber of the plasma source.[18] The recent thermal barrier concept in mirror fusion development[3,6] would require additional neutral beam injectors to pump out ions trapped in the thermal barrier region. Thus, there is one more spot for potential problems of arcing.

Studies about arcing involve a broad range of approaches[5,9,10,16] including thermionic emission, field emission, material, electrical contacts, gas discharges, breakdowns, and electrode components, etc.[13,14,23] If we really want to get a detailed analysis, then ionization and recombination processes in the boundary layer region must be included. A kinetic model for reacting gases[2,11] should thus be adopted in order to have a complete description. For most cases, however, a gross picture of thermodynamic heat balance may provide enough insight for the understanding of arcs. It is the later approach that we are using here.

II. ARC INITIATION

The formation of an arc is a study of the instability of plasma.[19,21,24] By taking into account the fact that arcs may lose and/or gain electrons or ions from time to time due to plasma interaction and current transport processes, we were able to establish a new criteria of arcing. The results have been reported at the 31st Gaseous Electronics Conference in Buffalo, NY. Schematically, the arc is assumed to come from the applied electric field and current between two electrodes with plasma flow inside.



If the arc, or more properly, the current-carrying column before constriction starts, is assumed to be a uniform cylinder with uniform electrical conductivity σ_a, constant arc temperature T_a, and if the heat transfer coefficient of flow around a cylinder h is known, the steady state problem can be solved by the following equations:

$$I = \pi R^2 \sigma_a E$$

$$\sigma_a = \sigma(T_a)$$

$$EI = 2\pi Rh(T_a - T_\infty)$$

Where E is electric field intensity, R is the arc radius. T_∞ is the ambient gas temperature.

The first equation is simply Ohm's law with electrical conductivity σ_a being a function of arc temperature T_a only. The last equation gives heat balance between Joule heating and the convective cooling due to the gas flow with T_∞ being the ambient gas temperature and h the heat transfer coefficient.

Note that only the transverse component of the arc is being considered here. By assuming the arc is cylindrically uniform the problem becomes essentially one-dimensional.

Once the field E or the current I is specified, the radius of an arc can be determined. Also, the arc characteristics which provides the E-I relationship is simply:

$$E = \left(\frac{4\pi}{\sigma_a}\right)^{1/3} \left[h(T_a - T_\infty)\right]^{2/3} \left(\frac{1}{I^{2/3}}\right)$$

which is obtained by eliminating R from the above equations.

By applying a simple perturbational method to these heat balance equations, we have established a new arcing criteria(12) which have been proven correct, and they will reduce to the conventional criteria in limiting cases.

Once an arc is formed, we like to study how arc radius R varies with external physical conditions, and how the current is related to the applied field in an arc. The task now is thus to characterize the arc as a function of the external parameters.

III. ELECTRICAL CONDUCTIVITY PROFILE

Again, by assuming that the arc is a cylinder with negligible axial variation and the dominant heat transfer process is conduction inside the cylinder and convection/radiation by the external flow at the outside edge, we have the following equation in the cylinder:

$$\frac{1}{r}\frac{d}{dr}\left(rK\frac{dT}{dr}\right) + \sigma E^2 = 0$$

where the angular and longitudinal variations have been neglected. K is the thermal conductivity and σE^2 is the Joule heating term. Here E is fixed externally and I is allowed to vary. Unless σ as function of either r or T is known, this equation is not complete.

Since approximately σ varies exponentially as function of temperature, a small perturbation in $\ln \sigma$ will produce some linear variation in T. The temperature profile can thus be assumed as:

$$T = T_a + \left(\frac{dT}{d\ln\sigma}\right)_a (\ln\sigma - \ln\sigma_a)$$

where "a" signifies the center of the arc, and both T_a and σ_a are assumed to be known.

Hence $T = T_a + \left(\frac{dT}{d\ln\sigma}\right)_a \ln\left(\frac{\sigma}{\sigma_a}\right)$

$$= T_a + T_a\left(\frac{1}{T_a}\right)\left(\frac{dT}{d\ln\sigma}\right)_a \ln\left(\frac{\sigma}{\sigma_a}\right)$$

$$= T_a + T_a\left(\frac{d\ln T_a}{d\ln\sigma_a}\right)\ln\left(\frac{\sigma}{\sigma_a}\right).$$

By assuming $= \frac{d\ln T_a}{d\ln\sigma_a}$ is a known constant, and defining

$$\tau = \frac{T}{T_a} - 1 ,$$

we get $\quad \tau = \eta\ln\left(\frac{\sigma}{\sigma_a}\right)$

or $\quad \sigma = \sigma_a e^{\tau/\eta}.$

If K is assumed to be a constant, say K_a, the thermal conductivity at the center of the arc where $T = T_a$, then the energy equation becomes:

$$\frac{K_a T_a}{r}\frac{d}{dr}\left(r\frac{d\tau}{dr}\right) + \sigma_a E^2 e^{\tau/\eta} = 0.$$

Defining

$$r_a = \left(\frac{8K_a T_a \eta}{\sigma_a E^2}\right)^{1/2},$$

this equation can be solved analytically as:

$$e^{\tau/\eta} = \sigma/\sigma_a = \left(1 + \frac{r^2}{r_a^2}\right)^{-2}.$$

At $r = 0$, $T = T_a$, $\tau = 0$, $\sigma = \sigma_a$.

At $r = r_a$, let $T = T_b$, the boundary temperature; $\sigma = \frac{\sigma_a}{4}$

$$e^{\tau/\eta} = \frac{1}{4}\ ; \quad \frac{\tau}{\eta} = -\ \ell n 4$$

$$\therefore T_b = (1 - \ell n 4 \eta)\ T_a.$$

If $\eta = 0.1$, $T_b = 0.86\ T_a$.

The temperature and electrical conductivity profiles are then determined, and r_a plays the role of the arc radius. Total current $I_\infty = \int_0^\infty \sigma E 2\pi r dr = \sigma_a E \pi r_a^{\ 2} = \left(\frac{8\pi K_a T_a \eta}{E}\right)$; $\quad \therefore I_\infty \sim E^{-1}$.

If we generalize this idea to assume

$$\frac{\sigma}{\sigma_a} = \frac{1}{\left(1+ \frac{r^2}{r_a^2}\right)^n}$$

then

$$I_\infty = \pi r_a^2\ \sigma_a E\left(\frac{1}{n-1}\right).$$

Define

$$(r_a)\ \text{eff.} = \frac{r_a}{\sqrt{n-1}}\ ,\ \text{then}$$

at $r = (r_a)_{\text{eff.}}$

$$\frac{\sigma}{\sigma_a} = e^{\tau/\eta} = \frac{1}{\left(1+ \frac{1}{n-1}\right)^n} = e^{\frac{1}{\eta}\left(\frac{T_b - T_a}{T_a}\right)}.$$

Call $\Delta T = T_a - T_b$,

$$\frac{\Delta T}{T_a} = \eta\ n\ \ell n\left(1+ \frac{1}{n-1}\right).$$

For $\eta = 0.1$, $\frac{\Delta T}{T_a}$ has the following values for various n's.

n	$\frac{\Delta T}{T_a}$
2	0.14
3	0.12
4	0.11
10	0.1
100	0.1
∞	0.1

This gives the temperature profile which is quite insensitive to the σ changes.

IV. T AS A FUNCTION OF σ

This model is basically quite good, except that to treat T as a function of $\ell n\sigma$ might sound like introducing an extra condition. If we write,

$$T = T_a + \left(\frac{dT}{d\sigma}\right)_a (\sigma - \sigma_a)$$

then $$T = T_a + \left(\frac{d\ell nT}{d\ell n\sigma}\right)_a \frac{T_a}{\sigma_a} (\sigma - \sigma_a)$$

Again, set $\eta = \frac{d\ell nT_a}{d\ell n\sigma_a}$

also let, $S = \frac{\sigma}{\sigma_a}$

then $T = T_a + \eta(S-1)\ T_a$,

$$\tau = \left(\frac{T}{T_a} - 1\right) = \eta(S-1),$$

The energy equation

$$\frac{1}{r}\ \frac{d}{dr}\left(rK\frac{dT}{dr}\right) + \sigma E^2 = 0 \text{ becomes}$$

$$\sigma_a SE^2 + K_a T_a n \frac{d}{rdr}\left(r\frac{dS}{dr}\right) = 0$$

or
$$S + \left(\frac{K_a T_a n}{\sigma_a E^2}\right) \frac{d}{rdr}\left(r\frac{dS}{dr}\right) = 0.$$

Set $\frac{r}{r_*} = x$; and $r_*^2 = \frac{K_a T_a n}{\sigma_a E^2}$

We get $S + \frac{1}{x}\ \frac{d}{dx}\left(x\frac{dS}{dx}\right) = 0$

or $xS'' + S' + xS = 0$

which is the Bessel equation. The solution of it are Bessel Functions of zeroth order:

$$S = C_1 J_0(x) + C_2 Y_0(x)$$

Since when $r = 0$, $\sigma = \sigma_a$, $S = 1$,

$C_1 = 1$, $C_2 = 0$.

Thus $S = J_0(x) = J_0\left(\frac{r}{r_*}\right)$

The conditions $S'\ (x=0)=0$ is automatically satisfied at $r=0$. When x is small:

$$J_0(x) \approx 1 - \frac{\frac{1}{4}x^2}{(1!)^2} + \frac{\left(\frac{1}{4}x^2\right)^2}{(2!)^2} - \frac{\left(\frac{1}{4}x^2\right)^3}{(3!)^2}$$

If we pick just the first three terms,

$$J_0(x) = \left(1 - \frac{1}{8}x^2\right)^2 = \left(1 + \frac{r^2}{8r*^2}\right)^2 = \left(1 - \frac{r^2}{r_a^2}\right)$$

where again $r_a^2 = 8r_*^2 = \frac{8K_a T_a n}{\sigma_a E^2}$, which is the same r_a defined previously.

And the solution $S = \frac{\sigma}{\sigma_a} \sim \left(1-\frac{r^2}{r_a^{\ 2}}\right)^2$ matches the previous solution

$\frac{\sigma}{\sigma_a} = \frac{1}{\left(1+r^2/r_a^{\ 2}\right)^2}$ exactly when r is small.

In all the above analyses, the thermal conductivity K is assumed to be equal to the known constant at the center of the arc K_a. Actually, if we define a thermal conductivity integral

$$\Phi = \int_0^T K(T)dT$$

when $K = K(T)$ is known, then

$$\frac{d\Phi}{dT} = K(T)$$

Thus the energy equation

$$\frac{1}{r}\frac{d}{dr}\left(rK\frac{dT}{dr}\right) + \sigma E^2 = 0$$

becomes

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\Phi}{dr}\right) + \sigma E^2 = 0.$$

Thus, if instead of using T, we set

$$\Phi = \Phi_a + \left(\frac{d\Phi}{d\,\ell n\,\sigma}\right)_a (\ell n\sigma - \ell n\sigma_a)$$

and define

$$\tau = \left(\frac{\Phi}{\Phi_a} - 1\right) = \eta\,\ell n\left(\frac{\sigma}{\sigma_a}\right)$$

where

$$\eta = \left(\frac{d\,\ell n\,\Phi}{d\,\ell n\,\sigma}\right)_a$$

then exactly the same solution will be obtained

$$\frac{\sigma}{\sigma_a} = e^{\tau/\eta} = \frac{1}{\left(1+r^2/r_a^{\ 2}\right)^2}$$

The temperature T is, however, being replaced by Φ_a and $r_a^{\ 2} = \frac{8\Phi_a\eta}{\sigma_a E^2}$

V. ARC RADIUS AND CHARACTERISTICS

Although the parameter r_a plays a role as the arc radius, the true arc boundary radius R_1 should be determined as follows:

$$\int_0^{R_1} (\sigma E^2)\, 2\pi \cdot r dr = 2\pi \cdot R_1 h\, (T_1 - T_\infty)$$

Physically, this means that the total heat conducted inside the cylinder has to be balanced by the cooling done by convection due to the external flow at the boundary. Where:

h = surface convective heat transfer coefficient of the arc

T_1 = arc surface temperature at R_1

R_1 = arc radius

T_∞ = ambient flow temperature.

Or, if cooling is mainly due to radiation, the right hand side should be replaced by Stefan-Boltzmann radiation law. Since the arcing data are readily available for a flow of convective plasma as in an MHD generator, we will concentrate on this case at present. A detailed study of radiation for an actual physical set-up requires more information about emissivity, absorptivity, geometrical viewing angles, etc.

The discrete contribution due to line-line radiation may prove to be quite significant as well. If we simply assume an isotropic radiation of the form $(T_1^4 - T_\infty{}^4)$ multiplying Stefan-Boltzmann constant and the collecting surface area and some other emissivity and viewing factors, we will find the result is almost the same as treating it as a $(T_1 - T_\infty)$ convective case with slight modification in the value of h.

For a cylindrical arc:

$$h = \frac{R_1 (0.26) K}{(2R_1)^{1.4}} \left(\frac{\rho_\infty u_\infty}{\mu}\right)^{0.6}$$

where ρ_∞ = flow density = (Kg/m^3)

μ = viscosity = (Kg/msec)

u_∞ = flow speed = (m/sec)

K = thermal conductivity = (Watt/m ^oK)

Using

$$\frac{\sigma}{\sigma_a} = e^{\tau/\eta} = \frac{1}{\left(1+r^2/r_a^{\ 2}\right)^2},$$

$$r_a^{\ 2} = \frac{8K_aT_a\eta}{\sigma_aE^2}$$

$$\int_0^{R_1} \sigma_aE^2 2\pi r \frac{1}{\left(1+r^2/r_a^{\ 2}\right)^2} dr = 2\pi R_1h(T_1-T_\infty)$$

becomes

$$\pi\sigma_aE^2r_a^{\ 2}\left[1-\frac{1}{1+R_1^{\ 2}/r_a^{\ 2}}\right] = 2\pi R_1h\left[T_a\left(1+\ \eta\ell n\frac{1}{\left(1+R_1^{\ 2}/r_a^{\ 2}\right)^2}\right)-T_\infty\right]$$

First, let us assume $R_1 \ll r_a$, then $\left(\frac{R_1^{\ 2}}{r_a^{\ 2}}\right)$ is a small quantity x. Thus

$\frac{1}{1+x} = 1-x$; and $\ell n\frac{1}{(1+x)^2} \sim -2x$. The equation reduces to

$$\pi r_a^{\ 2}\ \sigma_aE^2\left(\frac{R_1^{\ 2}}{r_a^{\ 2}}\right) = 2\pi R_1h\left[T_a\left(1-2\eta\frac{R_1^{\ 2}}{r_a^{\ 2}}\right)-T_\infty\right]$$

Since η is usually very small, we can further neglect the product $\left(\eta\frac{R_1^{\ 2}}{r_1^{\ 2}}\right)$.

Then it becomes simply

$$\pi\sigma_aE^2R_1^{\ 2} = 2\pi\ hR_1(T_a - T_\infty)$$

Physically, this means that the current density is uniformly $\sigma_a E$ over an area πR_1^2, and the arc temperature is just T_a. By substituting the formula for h into the equation, we get

$$\sigma_a E^2 = \frac{2(0.26)K}{(2R_1)^{1.4}} \left(\frac{\rho_\infty u_\infty}{\mu}\right)^{0.6} (T_a - T_\infty)$$

Therefore, other than some flow constants, this simple picture of arc provides us a relationship between R_1 and E: $R_1^{1.4} \sim E^{-2}$.

The arc current for this case is

$$I_1 = \int_0^{R_1} \sigma E 2\pi r dr = \pi \sigma_a E r_a^2 \left[1 - \frac{1}{1+R_1^2/r_a^2}\right]$$

for

$$\frac{R_1^2}{r_a^2} \ll 1,$$

$$I_1 \sim \pi \sigma_a E R_1^2,$$

$$I_1 \sim E \times (E^{-2/1.4})^2 \sim E^{-1.857}$$

Hence the arc characteristics are simply

$$E \sim I_1^{0.5385}$$

$$R_1 \sim I_1^{-0.7693}$$

These are the conventional results in the literature.[17] The arc radius can be calculated either by

$$(2R_1)^{1.4} = \frac{2(T_a - T_\infty)}{\sigma_a E^2} 0.26K \left(\frac{\rho_\infty u_\infty}{\mu}\right)^{0.6}$$

or,

$$R_1^{1.4} = \frac{2}{2^{1.4}} \quad \frac{r_a^2}{8\,\eta\, T_a} \quad (T_a - T_\infty)0.26 \left(\frac{\rho_\infty u_\infty}{\mu}\right)^{0.6}$$

However, these results hold only if $R_1 << r_a$. This is true only if T_a is not much higher than T_∞. The requirement $\left(\frac{R_1^2}{r_a^2} << 1\right)$ corresponds to approximately $(1 - T_\infty/T_a)\ Re^{0.6} << 1$, where Re is the Reynold's number $\left(\frac{\rho_\infty u_\infty R_1}{\mu}\right)$. Roughly if T_∞ = 2000 K, the regular MHD flow conditions (ρ_∞ = 0.12, u_∞ = 1000, $\mu = 6.35 \times 10^{-5}$) shows T_a has to be 2150^{0}K in order that the conventional formula be applicable.

In general, the heat balance equation is:

$$\sigma_a E^2 r_a^2 \left[1 - \frac{1}{1 + \frac{R_1^2}{r_a^2}}\right] = 2R_1 h \left[T_a\left(1 + \eta \ell n \frac{1}{\left(1 + \frac{R_1^2}{R_a^2}\right)^2}\right) - T_\infty\right]$$

which is,

$$1 - \frac{1}{1 + \frac{R_1^2}{r_a^2}} = 0.25 \times \frac{0.26}{2^{1.4}} \times \left(\frac{\rho_\infty u_\infty R_1}{\mu}\right)^{0.6} \left[\frac{1}{\eta}\left(1 - \frac{T_\infty}{T_a}\right) + \ell n \frac{1}{\left(1 + \frac{R_1^2}{r_a^2}\right)^2}\right]$$

By using the existing $\sigma(T)$ program, and using $K_a = 0.16 \times \left(\frac{T_a}{3000}\right)^{0.6}$, results shown in Figs. 1, 2 and 3 have been obtained for various arc temperatures T_a.

When T_a increases, the arc radius R_1 always decreases except for one extremely low arc temperature case where the traditional arc characteristics may hold. The ratio of R_1/r_a is almost always a constant, thus r_a can also be considered effectively the arc radius. And when T_a increases, R_1/r_a first starts to increase but after reaching certain temperature (2900^{o}K), the ratio decreases with increasing temperature. Only for the extremely low T_a = 2100^{o}K case, $R_1/r_a < 1$, for most of the other T_a values, R_1/r_a varies between 1 and 2. However, when T_a is sufficiently high say, at about 4100^{o}K, R_1/r_a drops back to be less than 1 again. Also, although R_1 still decreases with increasing T_a, when the arc temperature is that high, the decreasing rate of R_1 is so slow that the variation is almost undetectable. It thus makes sense to assume that the arc temperature is roughly, say 4300^{o}K, not higher.

The current has two formulas:

$$I_\infty = \int_o^\infty \sigma E 2\pi r dr = \frac{8\pi K_a T_a \eta}{E}$$

and

$$I_1 = \int_o^\infty \sigma E 2\pi r dr = \frac{8\pi K_a T_a \eta}{E}\left(1 - \frac{1}{1+R_1^2/r_a^2}\right)$$

If two arc spots are not too close to each other I_∞ should be the true arc current, otherwise I_1.

For the same E field, both I_∞ and I_1 increases as T_a increases. But for higher T_a, the increase rates become slower. The variation of I_1 further depends on the ratio R_1/r_a. When it gets steady, I_1 behaves the same way as I_∞. The logarithmic scale of the arc radius varies linearly with the log scale of the current, and the ratio R_1/r_a is also roughly a constant as a function of log current. The characteristics are thus,

$E \sim I_\infty^{-1}$ and $R_1 \sim I_\infty^{1.05}$.

VI. CONCLUSION

The electric arcing phenomenon has been studied from the energy balance point of view. By assuming a simple heat conduction process inside and convection/radiation outside an arc, we have determined the arc radius and its characteristics.

Although charge density is not an explicit parameter in the present formulation, it is believed that the analysis can be applied quite broadly, particularly to collisional dominant plasmas. For the case of rarefied plasma with extremely long mean free path, the fluid description loses much of its meaning. Detailed arcing criteria from the conductivity point of view can be found from a previous paper.[12]

The newly obtained arcing characteristics, while they will reduce back to the conventional properties such as $E \sim I^{0.5385}$ and $R \sim I^{-0.7693}$ in the limiting cases, are valid over a much wider temperature range. Depending on how closely two arc spots are separated, the arc current can be represented by I_1 or I_∞ as described in the paper. The arc characteristics are then given by the heat balance equation, or simply in terms of I_∞: $E \sim I_\infty^{-1}$ and $R_1 \sim I^{1.05}$.

Another significant finding of the present paper is the electrical conductivity profile of an arc. By using a parameter η, which is the ratio of ℓnT over $\ell n\sigma$, we are able to obtain an extremely simple formula of σ in terms of the arc radius r. Since for most laboratory plasmas particularly for MHD generators where low temperature plasma is used as the working fluid, the factor η as a constant is indeed a valid assumption, the simple electric conductivity profile obtained should be quite useful.

VII. ACKNOWLEDGMENT

The author is indebted to many colleagues for their help during the course of this work. In particular, he wants to thank G.A. Carlson, B.M. Boghosian, J.M. Fink, and G.W. Hamilton, among others for the discussion about thermal barrier studies for tandem mirror machines. He is also grateful to D.E. Baldwin for the plasma microinstability discussion. The author also wants to thank W. Kunkel, R. Pyle, and M. Vella, among others at Lawrence Berkeley Laboratory for the discussions about the Neutral Beam Project. Last, but not least, he liked to express his sincere appreciation to Walter Ng both for his technical help in computation and for his hospitality. The kind arrangements made by W. Ng and M. Harrison are greatly appreciated.

FIGURE CAPTIONS

Figure 1	Arc Radius vs Current
Figure 2	Field vs Current
Figure 3	Field vs Arc Radius

REFERENCES

1. Baldwin, D.E., B.G. Logan, and T.C. Simonen, Ed. Physics Basis for MFTF-B, UCID-18498, LLNL.

2. Baum, H. and T.M. Fang, "Kinetic Equations for a Chemically-Reacting Plasma", Physics of Fluids, 15, 1881, 1972.

3. Carlson, G.A., et al, Tandem Mirror Reactor with Thermal Barriers, UCRL-52836, LLNL.

4. Chen, M.M., "Some Elementary Considerations Concerning the Uniformity of Electrical Conduction Through Gases", Proceedings of 7th Symposium on Engineering Aspects of MHD, Princeton, NJ, 1966, pp.17.

5. Cobine, J.D., "Gaseous Conductors", Dover Publications, Inc., New York, 1958.

6. Coensgen, F.H., T.C. Simonen, A.K. Chargin, and B.G. Logan, TMX Upgrade Major Project Proposal, LLNL-Prop-172.

7. Cowley, M.D., "A Boundary-Layer Model for Balanced Arcs", Publication No. 67-6, July 1967, Fluid Mechanics Lab, Department of ME, M.I.T., Cambridge, MA.

8. Drouet, M.G., Beaudet, R., and Jutras, R., "Measurement of the Distributions of the Current in a Moving Arc at the Electrode Surface", AIAA Paper No. 74-713, July 1974.

9. Ecker, G., "Electrode Components of the Arc Discharge", Ergenbnisse der Exakten Naturwissenschaften Vol. 33, 1961.

10. Ecker, G., "Gas Discharge Theory", Advanced Plasma Theory ed. by Rosenbluth, Proceedings of the International School of Physics "Enrico Fermi", Varenna, Italy, July 9-12, 1962.

11. Fang, T.M., "H-Theorem and Kinetic Equations for a Reacting Gas", Journal of Plasma Physics 10, 425, 1973.

12. Fang, T.M., "Boundary Layer Thermal Effect in MHD Channel", 31st Annual Gaseous Electronics Conference, Buffalo, NY, 1978.

13. Finkelnburg, W., and Peters, Th., Encyclo, Phys. 28 (Spektrokpie II), 79, 1957.

14. Finkelnburg, W., and Naecker, H., Encyclo. Phys 22, 254, 1956.

15. Grunder, H.A., et al, Accelerator and Fusion Research Division Annual Report 1979, LBL-10720 UC034, LBL, UC, Berkeley.

16. Hougen, M.L. and McCune, J.E., "Magnetohydrodynamic Instabilities in a Weekly Ionized, Radiating Plasma", AIAA J., Vol. 9, No. 10, Oct. 1971, p. 1947.

17. Hsu, M.S.S., "Thermal Instabilities and Arcs in the MHD Boundary Layers", Proc. of 13th Symposium on Engineering Aspects of MHD, Palo Alto, CA, 1973.

18. Kunkel, W. private communication.

19. Messerle, H.K., M. Sakuntala and D. Trung, "Arc Transition in MHD Generator, J. Phys. D, J. Appl. Phys. G.B., Vol. 3, 1970, pp. 1080-1088.

20. Myers, T.W., and Roman, W.C., "Experimental Investigation of an Electric Arc in Transverse Aerodynamic and Magnetic Field", AIAA Journal, November 1967.

21. Oliver, D.A., "Constricted Discharge in Magnetohydrodynamic Plasma",15th Symposium on Engineering Aspects of MHD, 1975, AVCO Everett Research Lab., July, 1975.

22. Oliver, D.A., "Collapse of the Inter-Electrode Breakdown Arc in the Magnetic Field Direction", GTL Report No. 122, M.I.T., July 1975.

23. Pfender, P., "Electric Arcs and Arc Gas Heaters" Chapter 5, Gaseous Electronics Vol. 1, ed. by Hirsch & Oskam, Academic Press, 1978.

24. Simon, A., "Instability of a Partially Ionized Plasma in Crossed Electric & Magnetic Fields", Physics of Fluids, Vol. 6, No. 3, March 1963, pp.382-388.

25. Unkel, W., C.H. Kruger, and J.K. Koester, "Axial Field Limitations in MHD Generators", Proc. Six Int'l. Conference on MHD Electrical Power Generation, Washington, D.C., June 1975.

26. Von Engel, A., "Ionized Gases", Oxford University Press (Clarendon), 1965.

27. Wright, J.K., "A Temperature Instability in MHD Flow", Proc. Phys. Soc., 1963, Vol. 81, pp. 498.

1656x

ARC RADIUS VS CURRENT

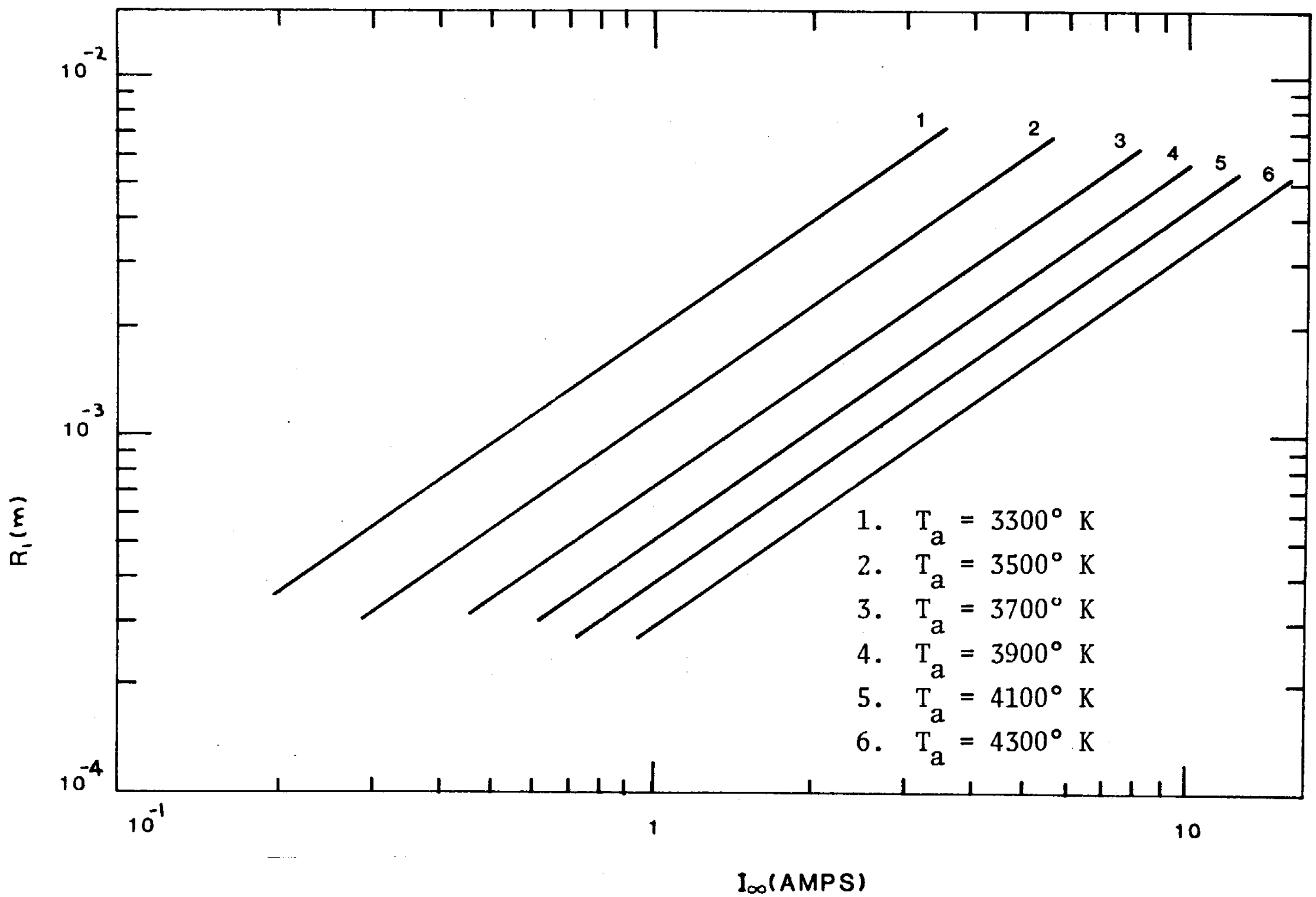


Fig. 1

FIELD VS CURRENT

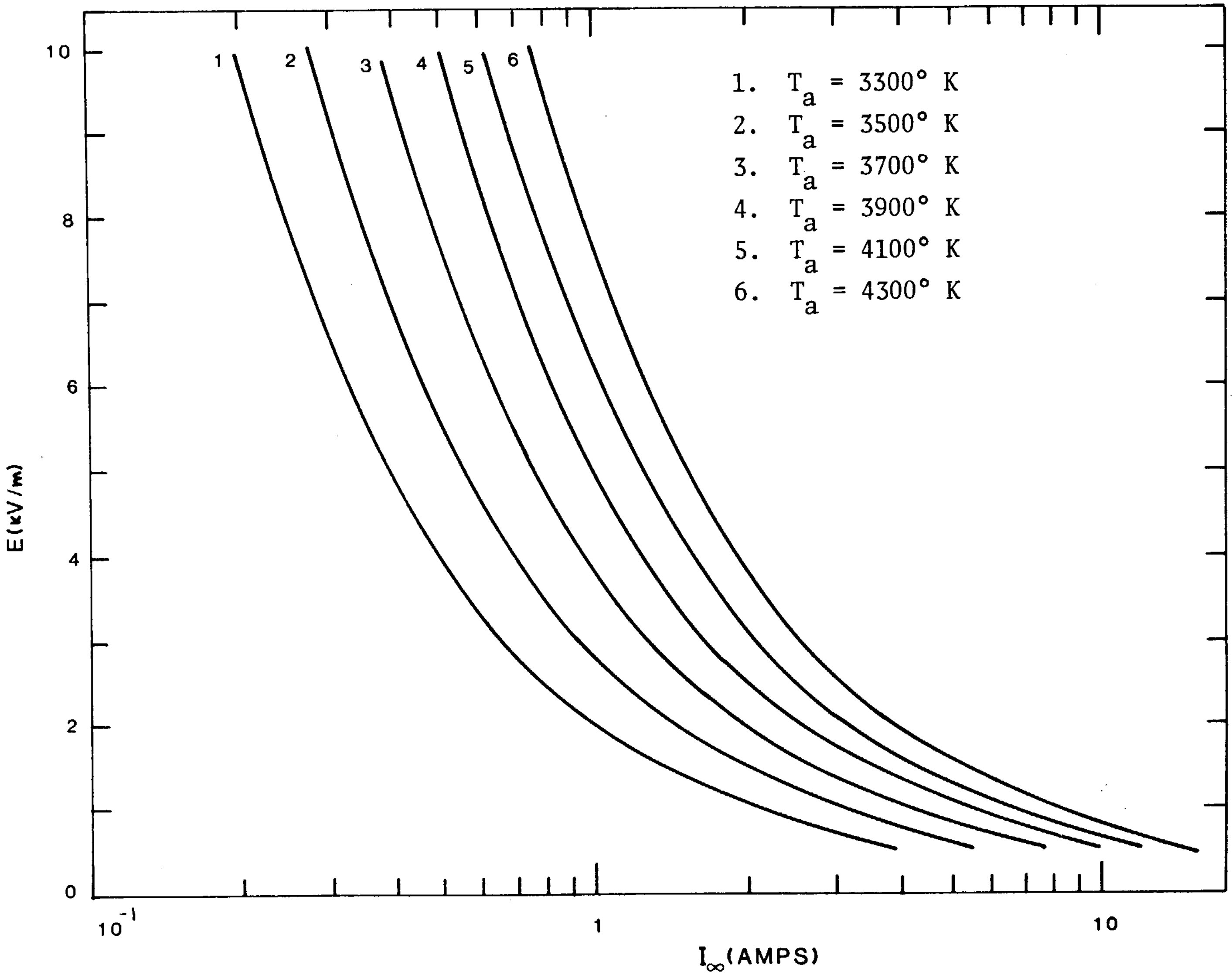


Fig. 2

FIELD VS ARC RADIUS

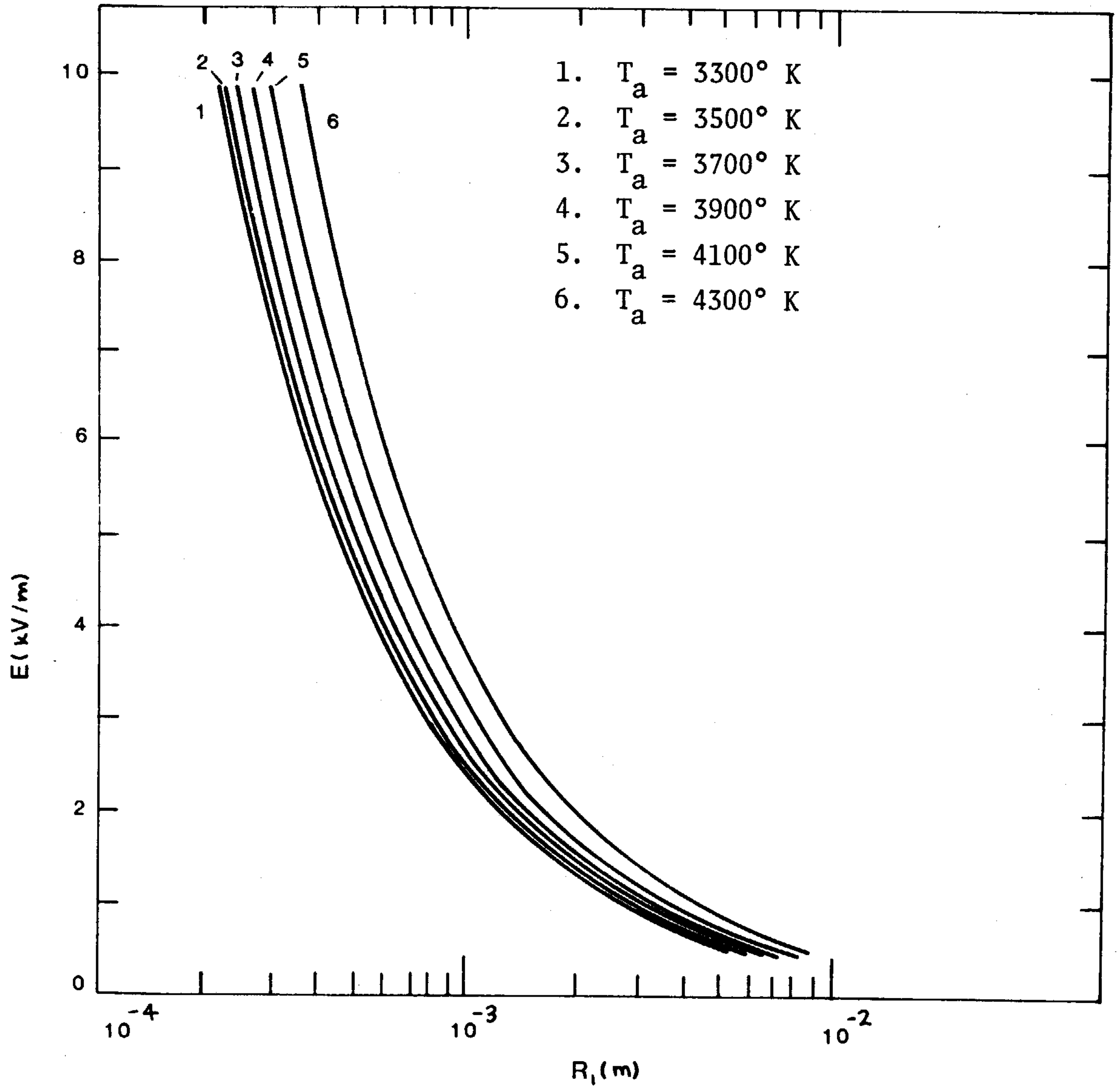


Fig. 3